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Transient processes under dynamic excitation of a coherent population trapping resonance*

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Abstract. **It is shown for the first time that under dynamic excitation of a coherent population trapping resonance in Rb vapours at different bichromatic pump modulation frequencies from a few tens of hertz and higher, the resonance is dramatically deformed as a result of emerging intensity oscillations of radiation transmitted through an Rb vapour cell. A significant change in the shape of the resonance under its dynamic excitation is confirmed experimentally and theoretically. A possible impact of the identified changes in the shape of the coherent population trapping resonance on the stability of an atomic clock is qualitatively discussed.**

Keywords: *coherent population trapping resonance, atomic clock, dynamic excitation of the atomic system, transient processes in the atomic system.*

1. Introduction

A coherent population trapping (CPT) resonance in a three-level atomic Λ system is formed by modulating the frequency difference of a bichromatic optical pump field [1]. An increase in the modulation frequency up to some optimum value (on the order of several kilohertz [2–4]) improves the signal/noise ratio and the stability of an atomic clock employing this resonance. On the other hand, it is known that under dynamic excitation of a CPT resonance with the characteristic times that are less than the time of coherent interaction of atoms with the pump field [5], there arise significant changes in the resonance amplitude [6], and at the trailing edge of the signal during the resonance detection there appear oscillations due to beats between the pump field and the relaxing field emitted by the atomic transition [6–8]. In the limiting case of dynamic excitation – a step change in the frequency difference of the pump field – such oscillations are harmonic and their frequency is exactly equal to the detuning of the bichromatic pump frequency from the atomic hyperfine transition frequency of the ground state of active atoms [7, 8]. This phenomenon can be a key tool in implementing a frequency standard, whose operating principle is to measure the oscillation frequency and to compared it with the hyperfine splitting frequency [8, 9].

In the case of a smooth dynamic change in the frequency difference of the bichromatic pump, the oscillations at the trailing edge of the signal during the CPT resonance measurement exhibit a pronounced anharmonic behaviour [5]. However, the manifestations of these oscillations in a wide frequency range of changes in the mentioned frequency difference have so far remained unstudied, and it has not been clear how they may affect the central part of the CPT resonance and hence the stability of the atomic clock.

In this paper, we have studied for the first time experimentally and theoretically transient processes under dynamic excitation of the CPT resonance in the Λ transition of the D_1 line of ^{87}Rb atoms ($F_g = 1{,}2 \rightarrow F_e = 2$) over a wide range of different bichromatic pump frequencies and have shown that relaxing oscillations arising at the trailing edge of the signal during the CPT resonance registration affect the shape of the resonance.

2. Theoretical model

The formation of the CPT resonance was studied theoretically using a simplified model – a three-level Λ system in a bichromatic field (Fig. 1). Dynamics of the formation of the CPT resonance was investigated with the help of the equations for the atomic density matrix, which in the resonance approximation have the form:

$$\frac{\partial\rho_{21}}{\partial t} = -[\varGamma_0 + \mathrm{i}(\delta_2 - \delta_1)]\rho_{21} - \mathrm{i}\varOmega_1\rho_{23} + \mathrm{i}\varOmega_2^*\rho_{31},$$

$$\frac{\partial\rho_{31}}{\partial t} = -(\gamma_{\mathrm{opt}} + \mathrm{i}\delta_1)\rho_{31} + \mathrm{i}\varOmega_1(\rho_{11} - \rho_{33}) + \mathrm{i}\varOmega_2\rho_{21},$$

$$\frac{\partial\rho_{32}}{\partial t} = -(\gamma_{\mathrm{opt}} + \mathrm{i}\delta_2)\rho_{32} + \mathrm{i}\varOmega_2(\rho_{22} - \rho_{33}) + \mathrm{i}\varOmega_1\rho_{12},$$

$$\frac{\partial\rho_{11}}{\partial t} = \frac{\gamma_{\mathrm{sp}}}{2}\rho_{33} + \frac{\varGamma_0}{2}\mathrm{tr}[\hat{\rho}] - \varGamma_0\rho_{11} - \mathrm{i}\varOmega_1\rho_{13} + \mathrm{i}\varOmega_1^*\rho_{31}, \qquad (1)$$

$$\frac{\partial\rho_{22}}{\partial t} = \frac{\gamma_{\mathrm{sp}}}{2}\rho_{33} + \frac{\varGamma_0}{2}\mathrm{tr}[\hat{\rho}] - \varGamma_0\rho_{22} - \mathrm{i}\varOmega_2\rho_{23} + \mathrm{i}\varOmega_2^*\rho_{32},$$

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$$\frac{\partial \rho_{33}}{\partial t} = -(\gamma_{sp} + \Gamma_0)\rho_{33} + \mathrm{i}\Omega_1\rho_{13} + \mathrm{i}\Omega_2\rho_{23} - \mathrm{i}\Omega_1^*\rho_{31} - \mathrm{i}\Omega_2^*\rho_{32},$$

$$\rho_{12} = \rho_{21}^*,\ \ \rho_{13} = \rho_{31}^*,\ \ \rho_{23} = \rho_{32}^*,$$

$$\mathrm{tr}[\hat{\rho}] = \rho_{11} + \rho_{22} + \rho_{33} = 1,$$

where $\Omega_{1,2}$ are the Rabi frequencies; γ_{sp} is the rate of the spontaneous decay of the upper level $|3\rangle$; γ_{opt} is the total decoherence rate of optical transitions $|1\rangle \to |3\rangle$ and $|2\rangle \to |3\rangle$; Γ_0 is the relaxation rate at lower energy levels $|1\rangle$ and $|2\rangle$ to the equilibrium isotropic state $(|1\rangle\langle 1| + |2\rangle\langle 2|)/2$; and $\delta_k = \omega_k - \omega_{3k}$ ($k = 1, 2$) is the frequency detuning to the kth field from the frequency of the corresponding resonant transition. To solve the system of equations (1) we used the method described in detail in our paper [10], which allows one to calculate the periodic steady state without considering the problem with initial conditions and without the use of the Fourier transform.

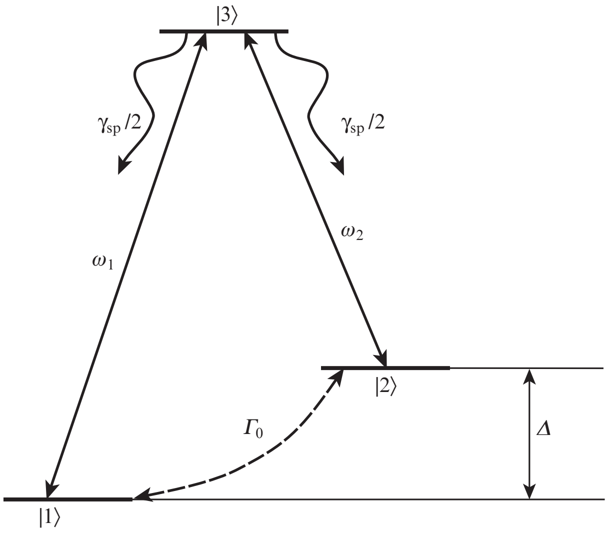

Figure 1. Three level Λ-type system in a bichromatic field.

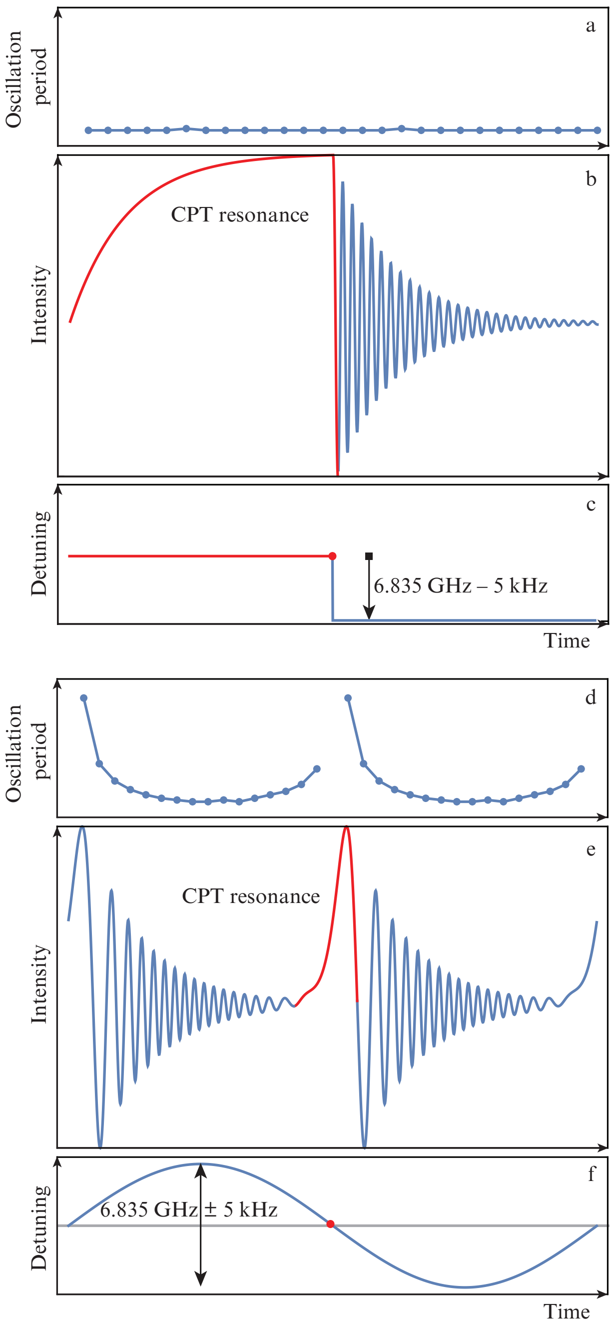

Figure 2. Calculated time dependences of the intensity of radiation transmitted through the Rb vapour cell under (a–c) stepwise and (d–f) harmonic CPT resonance excitation.

Figure 2b shows the calculated dependence of the intensity of radiation transmitted through a rubidium vapour cell on the time under stepwise excitation of the CPT resonance (Fig. 2c). It can be seen that the stepwise excitation of the CPT resonance leads to the formation of a damping oscillation with a constant period (Fig. 2a), which is consistent with the results of Ref. [8]. When the bichromatic pump frequencies smoothly change in accordance with the periodic law (Fig. 2f), the intensity oscillations of radiation passed through the cell exhibit an anharmonic behaviour (Fig. 2e), which is consistent with the results of [5].

Figure 3 shows the calculated dependence of the intensity of radiation transmitted through the rubidium vapour cell at different frequencies of the harmonic CPT resonance excitation. In order to compare in the same figure the behaviour of the oscillations whose frequencies can differ by two orders of magnitude, the abscissa shows the phase of the modulation signal at different modulation frequencies. One can see from Fig. 3 that a change in the excitation frequency from 4 to 400 Hz leads to a significant change not only in the oscillation at the trailing stage of the signal in the CPT resonance, but also in the central part of the CPT resonance – with increasing excitation frequency, its amplitude decreases, the width increases, and the rising edge of the signal during the resonance detection becomes more gently sloping as compared with its trailing edge. Note that oscillations at the trailing edge of the signal during the CPT resonance registration begin to appear at frequencies of a few tens of hertz, and with a further increase in the frequency these oscillations noticeably deform the CPT resonance. At low modula-

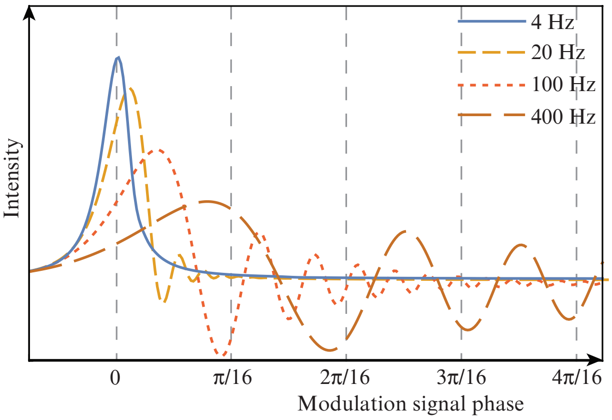

Figure 3. Calculated dependences of the intensity of radiation transmitted through the cell on the phase of the modulation signal at different modulation frequencies.

tion frequencies (few hertz), the shape of the resonance is described by the Lorentz function, which corresponds to the stationary case [11].

3. Experiment

Experimental studies of transient processes under dynamic excitation of the CPT resonance were performed using the setup shown in Fig. 4. The current of a single-frequency vertical-cavity surface-emitting pump laser (VCSEL) was modulated with a frequency of 3.417 GHz, obtained by a frequency synthesiser (Phase Matrix) and a reference quartz oscillator (RQO, 10 MHz), which led to the appearance (in the spectrum of the laser radiation) of two sideband frequencies detuned the centre frequency of the laser by ±3.417 GHz. The difference between these sideband frequencies corresponded to the frequency of the transition between the hyperfine splitting levels of the ground state of ^{87}Rb. For the CPT resonance to be formed, the difference of the sideband frequencies was modulated with a frequency which can be varied in the range of 0.1 – 400 Hz and with an amplitude of 2 kHz. The polarisation of the laser radiation was converted from linear to circular with the help of a $\lambda/4$ plate. A pump beam of 100-mW power and 0.4-mm diameter passed through a ^{87}Rb vapour spherical optical cell having a diameter of 13 mm and an antirelaxation coating on the inner surface of the cell, and its output power was measured with a photodetector (PD). The pump laser and the optical cell were thermostable, their temperature instability not exceeding 10^{-3} °C. For the protection from an external magnetic field, the optical cell was placed in a three-layer magnetic shield. The operating modes of the modules of the experimental setup were electronically controlled with a PXI National Instruments system.

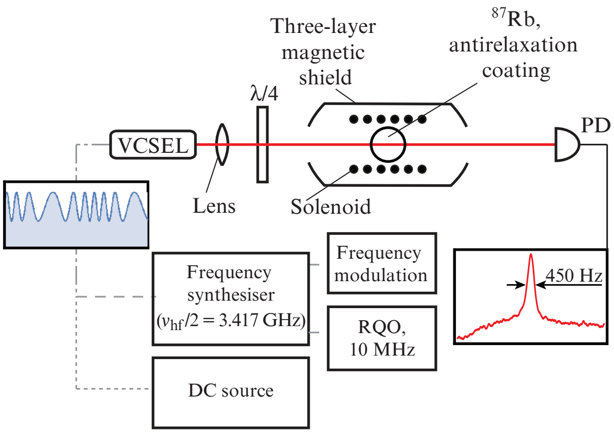

Figure 4. Scheme of the experimental setup.

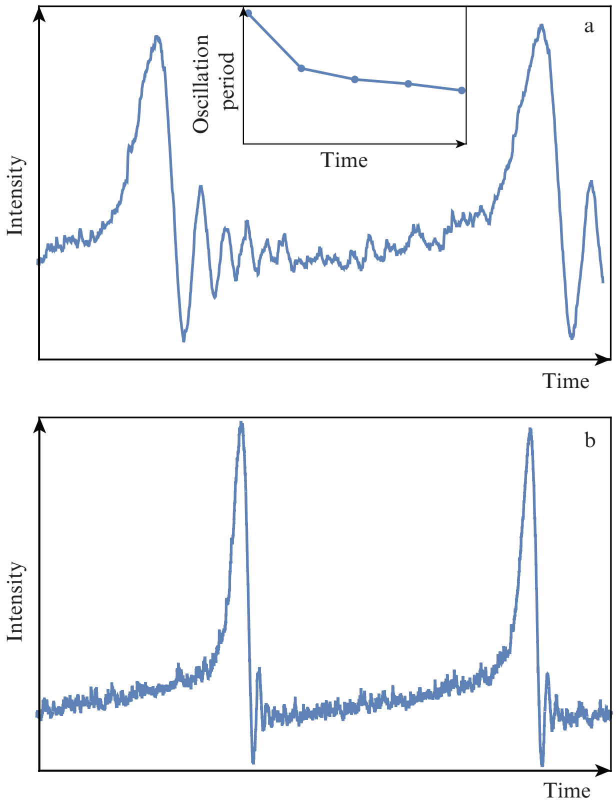

Figure 5. Experimental time dependence of the intensity of radiation transmitted through the rubidium vapour cell at a modulation frequency of (a) 100 and (b) 20 Hz.

Under relatively low (with frequencies in the range of 0.1 – 4 Hz) excitation of the CPT resonance we observed a resonance of 450 Hz width, with no oscillations at the trailing edge. With increasing excitation frequency, in the recorded time dependence of the emission intensity (Fig. 5) there appear oscillations, the nature of which is well correlated with the calculated curves shown in Fig. 3.

4. Conclusions

The studies have revealed a characteristic range (10 – 20 Hz) of different bichromatic pump modulation frequencies, in which intensity oscillations appear at the trailing edge of the signal during the CPT resonance registration. With a further increase in the modulation frequency, the transient processes of the quantum system are enhanced, which is manifested in an increase in the oscillations. They lead to an increase in the steepness of the trailing edge of the resonance as compared to its leading edge and to a decrease in the CPT resonance amplitude as evidenced by our modelling and experimental data obtained. Significant deformation of the CPT resonance shape with increasing modulation frequency of the frequency difference of the bichromatic pump limits the modulation frequency by some optimal value, at which the quantum frequency standard based on the CPT resonance is characterised by the best stability [2–4]. This optimum modulation frequency is the result of a compromise between an improved signal/noise ratio and a broadened CPT resonance, which occur simultaneously with increasing modulation frequency. Thus, in the present work we have shown for the first time that transient processes, manifested in the reduction of the CPT resonance amplitude and in the occurrence of relaxing oscillations at the trailing edge of the signal during the CPT resonance detection, lead to deformation of the CPT resonance shape, and with increasing modulation bichromatic pump frequency, this deformation becomes more pronounced.

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